Kepler, Newton, and laws of motion

First: A Little History

Geocentric vs. heliocentric model for solar system (sec. 2.2-2.4)

The only history in this course is this progression:

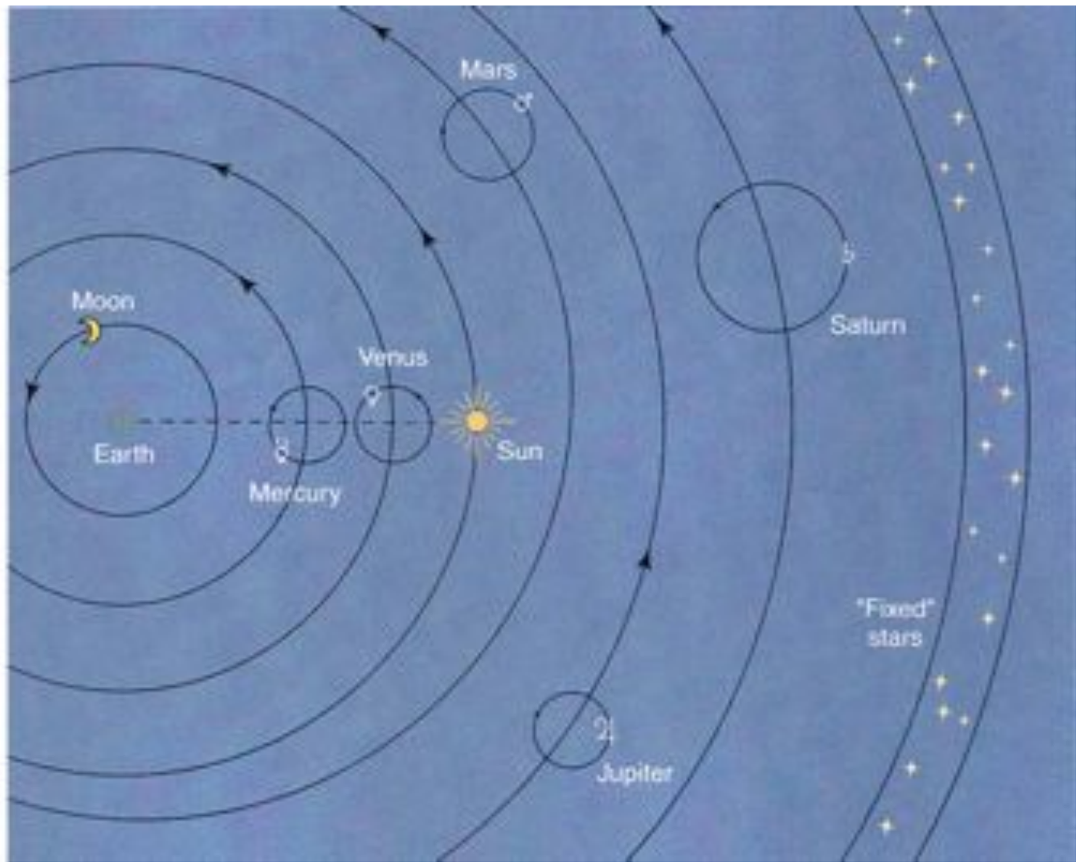
Aristotle (~350 BC)
Ptolemy (~140 AD)
…
Copernicus (~1500 AD)
Galileo (~1600)
Tycho Brahe (~1600)
Kepler (~1600, sec. 2.5)
Newton (~1700, sec. 2.6).

The major transition that this series of names represents:

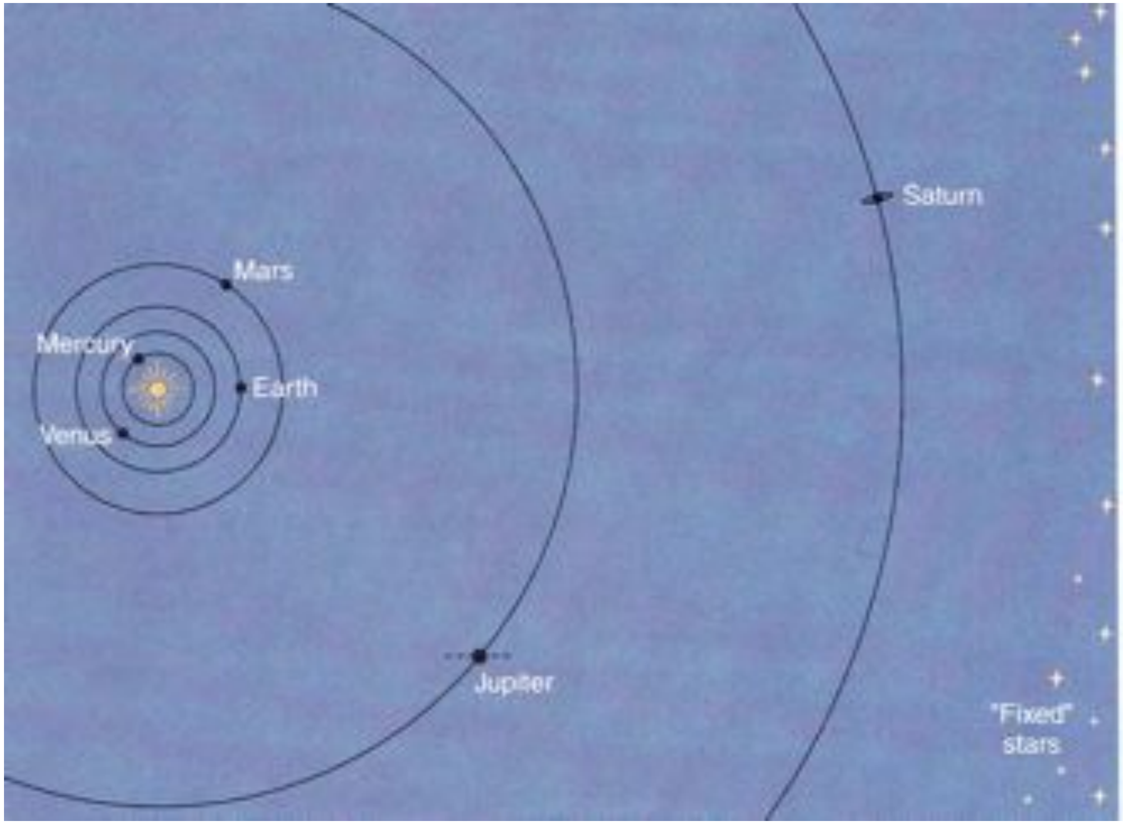
Geocentric model
(Ptolemy, epicycles, planets and Sun orbit the Earth)
→ ***Heliocentric model***
(Copernicus, planets orbit the Sun)

Geocentric Model

The solar system as conceived by Ptolemaic astronomers between about 100 and 1500. Ptolemaic astronomers made rough predictions of planetary motions, using a theory in which the Sun and other planets moved in circular orbits around a stationary, central Earth. Superimposed on the larger orbits were smaller circular motions called epicycles, introduced to try to make the theory more accurate.



Heliocentric Model



The solar system as it might have been conceived around 1700, at the end of the Copernican revolution. The diagram shows the orbits of the 10 known planets to true scale. The view is correct except that the outermost planets (Uranus, Neptune, and Pluto) and the asteroids had not yet been discovered. Compare with Figure 3–2 to see the change from the Ptolemaic view.

Kepler's Laws

Empirical, based on observations;
NOT a theory (in the sense of Newton's laws).

So they are "laws" in the sense of ***formulas that express some regularity or correlation***, but they don't _explain_ the observed phenomena in terms of something more basic.

Kepler's 1st law:

→ 1. <u>Orbits of planets are *ellipses*</u> (not circles), with Sun at one focus.

Must get used to terms

period (time for one orbit),
semimajor axis ("size" of orbit),
eccentricity (how "elongated" the orbit is),
perihelion (position of smallest distance to Sun),
aphelion (position of greatest distance to Sun)

<u>Examples</u>: comets, planets:

Importance of 1st law:

→ *Escaping from the assumption of perfect circles for orbits was a major leap, that even Copernicus was unwilling to take.*

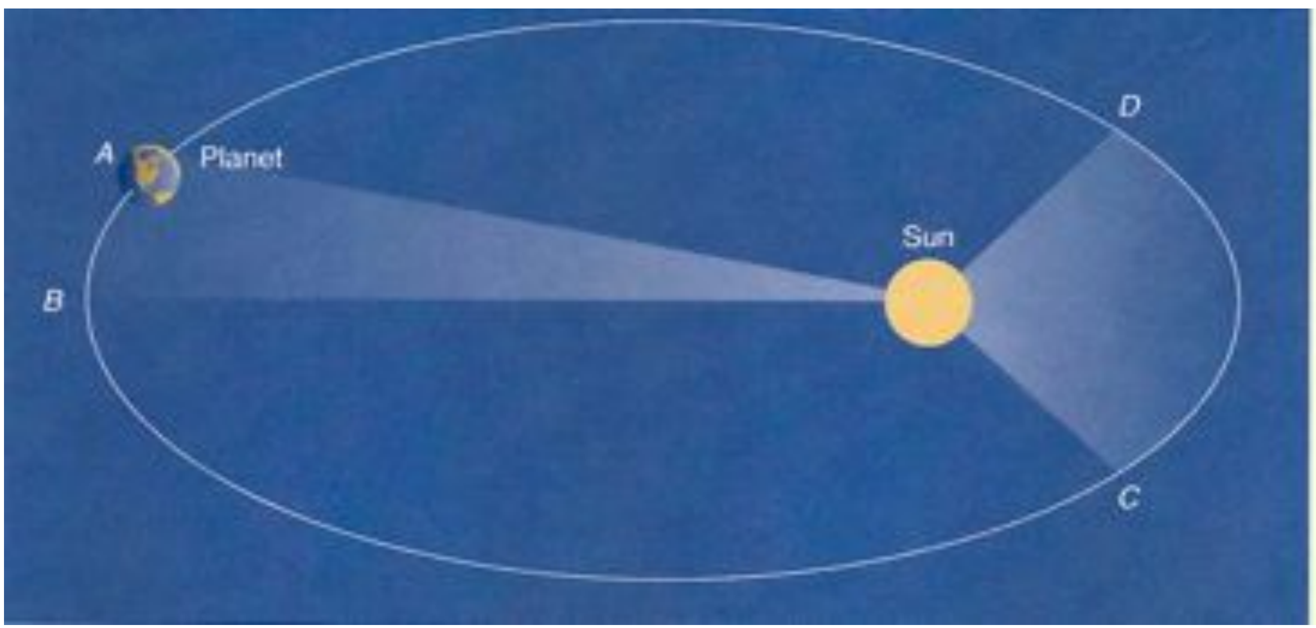
Kepler's 2nd law:

➞ 2. **Equal areas swept out in equal times**

Simpler: <u>Planets move faster when closer to the sun.</u>

Once the concept of gravity is included, this statement is nearly obvious.

Good example: comets (very eccentric orbits, explained in class).



Kepler's second law of planetary motion. The orbit sweeps out an ellipse where an imaginary line connecting the planet to the Sun sweeps out equal areas in equal time intervals. The time taken to move from *A* to *B* equals the time taken to move from *C* to *D*. In other words, planets travel faster when they are close to the Sun and more slowly when they are far from the Sun. The true planet orbits are much closer to circles, and the speed only changes by a small percentage along the orbit.

Kepler's 3rd law (the useful one)

- *Square of the period "P" is proportional to the cube of the semimajor axis "a" :*

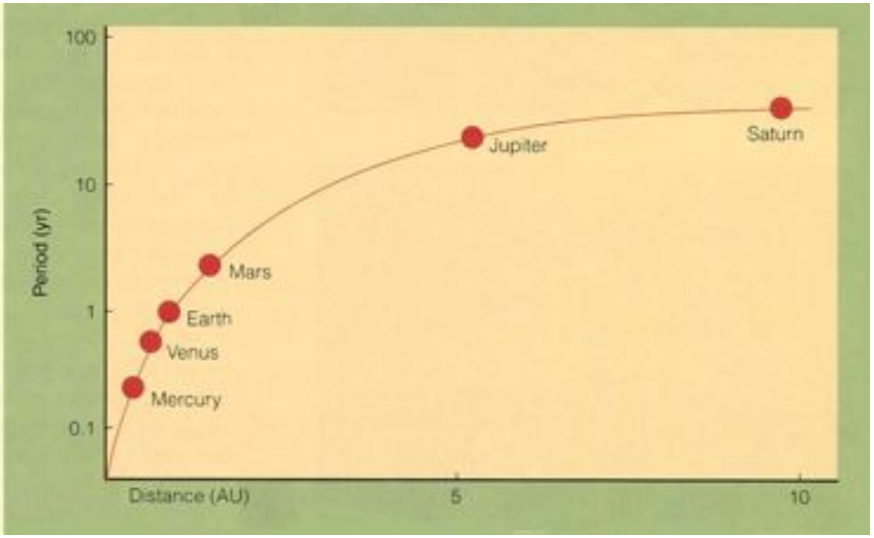
→ $P^2 = a^3$

IF P is expressed in Earth years and "a" is in units of A.U. (astronomical unit; average distance from Earth to Sun).

A graph of the periods vs. the distances from the sun (a) is shown below for the planets

(Absolute size of A.U. unit determined from radar observations of Venus and Mercury, and other methods--see textbook.)

Kepler's third law of planetary motion. The period of a planet's orbit increases with increasing distance from the Sun. Planets discovered after the invention of the telescope obey this law, too. Notice that according to Kepler's law, planets can have properties that place them *anywhere* on this curve. The planets of the solar system have a particular pattern in their spacing from the Sun.



→ Examples of use of Kepler's 3rd law:

1. The planet Saturn has a period of about 30 years; how far is it from the Sun?

Answer: Using $P^2 = a^3$, with P = 30 yr,

$$a = (30)^{2/3} = ((30)^2)^{1/3} = (900)^{1/3} \sim 10\text{AU}.$$

2. An object is observed orbiting the Sun in an orbit of semimajor axis = 4 AU. How long is its year (period)?

[Note: *This is as tough as the math will get in this class.]*

3. Given any single absolute distance in our solar system, such as radar-determined distance from Earth to Venus, Kepler's 3rd law gives us the sizes of the orbits of all the planets (and other objects), because we can easily observe their *periods.*

This is the basis for sec. 2.6 on "Distances in the Solar System."

Next time:

Newton’s Laws of Motion and Gravity

Newton's 3 laws of motion

1. ***Every body continues in a state of rest or uniform motion (constant velocity) in a straight line unless acted on by a force.***
(A deeper statement of this law is that momentum (mass x velocity) is a conserved quantity in our world, for unknown reasons.)
This tendency to keep moving or keep still is called "*inertia*."

2. *Acceleration* (change in speed or direction) *of object is proportional to: applied force F divided by the mass of the object m*
i.e. a = F/m or (more usual) F = ma
This law allows you to calculate the motion of an object, if you know the force acting on it. <u>This is how we calculate the motions of objects in physics and astronomy, and why the 2nd law is by far the most important one.</u>

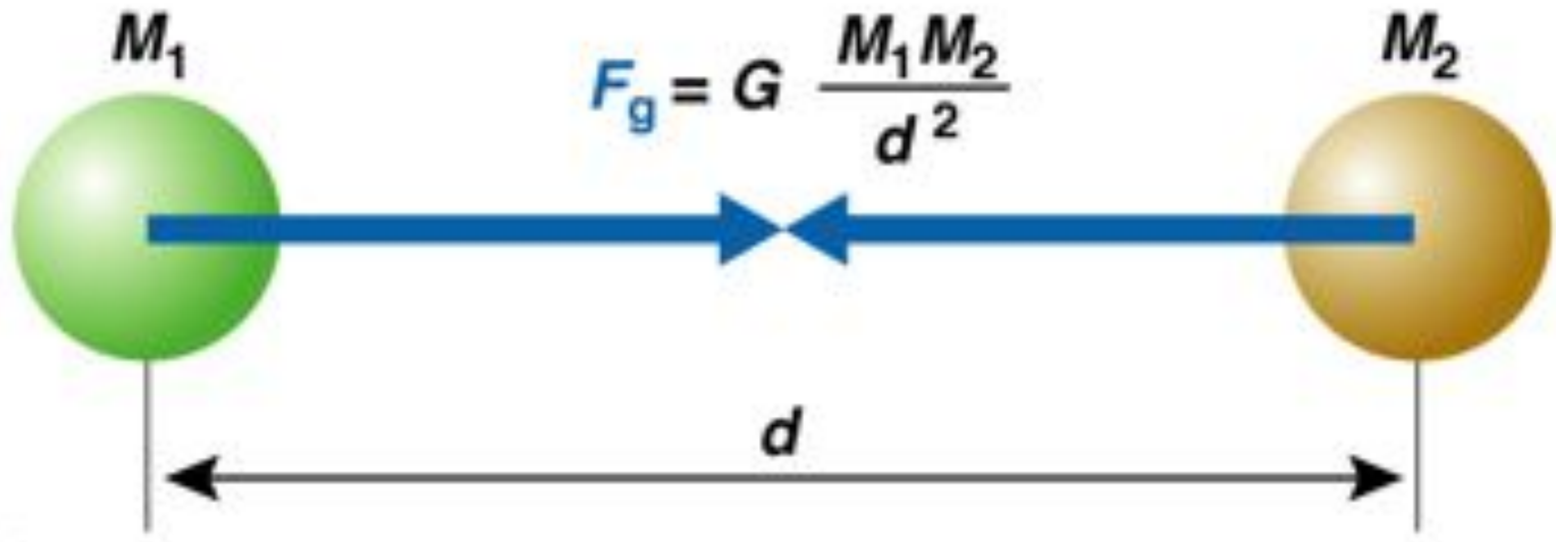
3. *To every action, there is an equal and opposite reaction*, i.e. forces are mutual. A more useful equivalent statement is that *interacting objects exchange momentum through equal and opposite forces.*

Newton's Law of Gravity

1. Every mass attracts every other mass.

2. Attraction is directly proportional to the product of their masses.

3. Attraction is inversely proportional to the square of the distance between their centers.

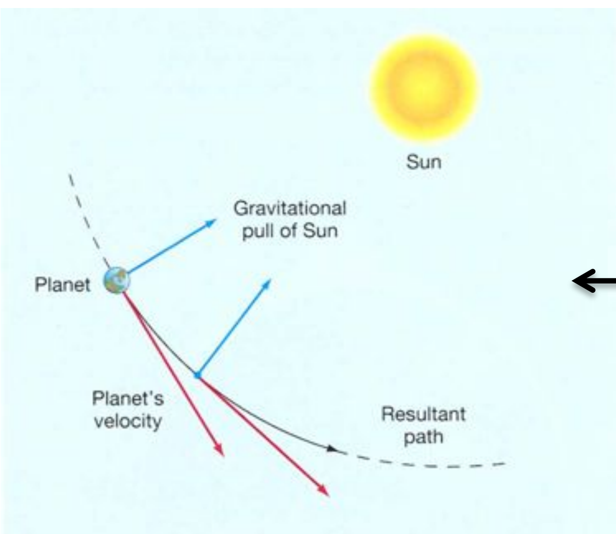


Newton's Law of Gravity (cont'd)

→ $F_{grav} = G\, m_1 m_2 / d$

G = "gravitational constant"
(measured; you don't need to know it)

Notice this is an "inverse square law" (right illus.). ⟶



▲ **FIGURE 2.24 Solar Gravity** The Sun's inward pull of gravity on a planet competes with the planet's tendency to continue moving in a straight line. These two effects combine, causing the planet to move smoothly along an intermediate path, which continually "falls around" the Sun. This unending "tug-of-war" between the Sun's gravity and the planet's inertia results in a stable orbit.

⟵ Orbits of planets (and everything else) are a balance between the moving object's tendency to move in a straight line at constant speed (Newton's 1st law) and the gravitational pull of the other object (see left).

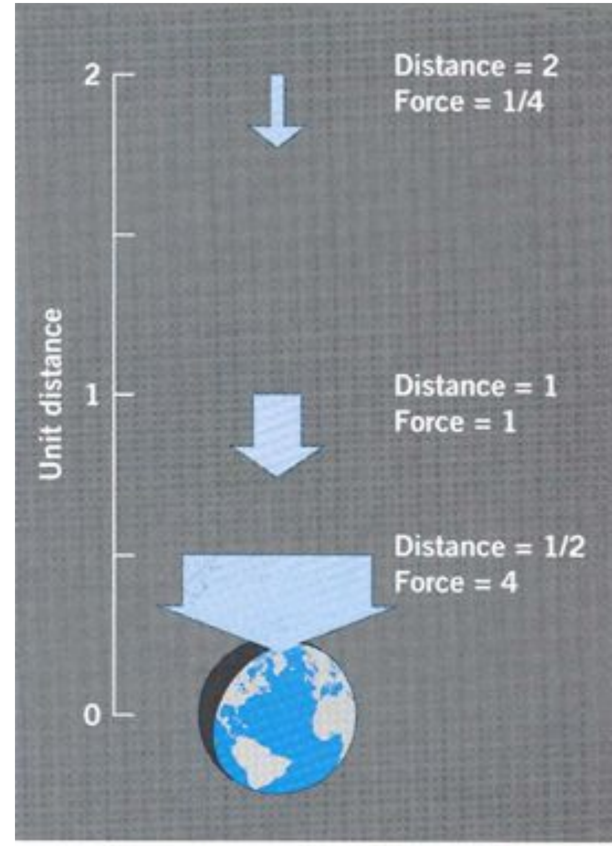


FIGURE 4.17 Moving the same mass at three different relative distances from the earth. For each distance, the thickness of the arrow indicates the relative amount of the gravitational force between the mass and the earth.

Finding the Masses of Astronomical Objects: Newton's Form of Kepler's 3rd Law

From Newton's laws of motion and Newton's law of gravity, Kepler's laws can be derived: "It can be shown" that all closed orbits are ellipses, that the orbital motion is faster when the two objects are closer to each other (Kepler's 2nd law), and Kepler's 3rd law, the most important result.

Kepler's third law now contains a new term:

⇨ $P^2 = a^3/(m_1 + m_2)$ → ***Newton's form of Kepler's 3rd law.***

(Masses expressed in units of solar masses; period in years, a in AU)

We will use this over and over--it is the only way we can get masses directly.

Newton's laws are *general*

We can calculate the orbit of an asteroid heading toward the Earth, the evolution of clusters of stars, of millions of galaxies in an expanding universe, of a hot gas in a magnetic field, and almost everything else, although in general this is so difficult that you can only get computer solutions.

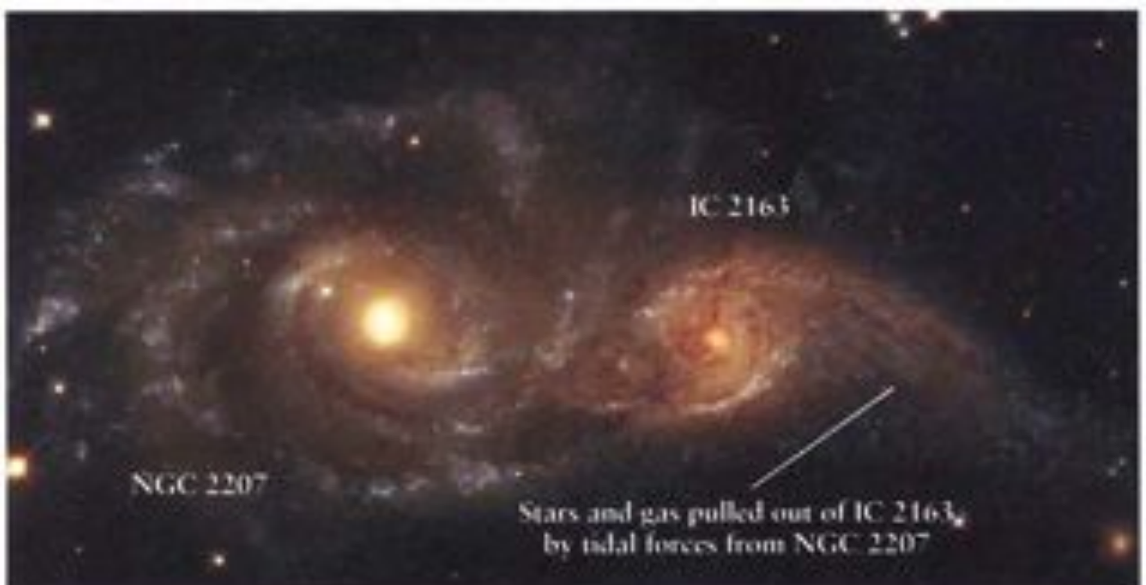
A few examples are given here and on the next slide.

Examples:

- Earth's orbital period (1 year) and average distance (1 AU) tell us the Sun's mass (think: why don't you need to know the Earth's mass for this purpose?
- Orbital period and distance of a satellite from Earth tell us Earth's mass.
- Orbital period and distance of a moon of Jupiter tell us Jupiter's mass.
- This is how "black holes" were discovered to actually exist (later in course), and how the masses of planets orbiting other stars are determined.
- Motion of stars in galaxies reveals the existence of invisible mass, or "dark matter," whose nature remains unknown.

A complex example of the use of Newton's laws: Illustration below shows effect of gravitational forces between two *galaxies* that are in the early stages of collisional *merging*. Solving Newton's laws for *millions* of stars and for the gas within these galaxies, we can actually make models for such phenomena that show how tidal forces are distorting these galaxies.

This example shows you that some orbits can decay, leading to merging of objects. We will see this again when we discuss the cannibalism of planets by their parent stars.



Tidal Forces on a Galaxy For millions of years the galaxies NGC 2207 and IC 2163 have been moving ponderously past each other. The larger galaxy's tremendous tidal forces have drawn a streamer of material a hundred thousand light-years long out of IC 2163. If you lived on a planet orbiting a star within this streamer, you would have a magnificent view of both galaxies. NGC 2207 and IC 2163 are respectively 143,000 light-years and 101,000 light-years in diameter. Both galaxies are 114 million light-years away in the constellation Canis Major. (NASA and the Hubble Heritage Team, AURA/STScI)

End of material about orbits under gravity

How else can we learn about astronomical objects?
All we get from them is their *light*, hence the next two chapters (3 and 4) are entirely concerned with how we can analyze light.

We will only cover chapter 3 for the first exam